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13. ABSTRACT *(Maximum 200 words)*

The objective of this investigation was to study the dynamics of the jet-mixing layer using a unique experimental apparatus in conjunction with Proper Orthogonal Decomposition (POD) techniques. The experiments utilize 138 hot-wires in the mixing layer of an axisymmetric jet to simultaneously resolve the instantaneous stream wise velocity field at all locations. The POD is then applied to a double Fourier transform in time and azimuthal direction of the two-point velocity correlation tensor.

Measurements covered all the potential core region of the jet from 2 to 6 diameters downstream at various high Reynolds numbers, 78, 400 to 156, 800, and the far field region from 21 to 69 diameters downstream, at Reynolds numbers from 40,000 to 84,700. The results both illustrate the limitations of the previous work, and point the way for a significant breakthrough in our understanding of free shear flows.

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POD INVESTIGATION INTO THE DYNAMICS OF THE TURBULENT JET

AFOSR GRANT F49620-98-1-0143

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Abstract

The objective of this investigation was to study the dynamics of the jet mixing layer using a unique experimental apparatus in conjunction with Proper Orthogonal Decomposition (POD) techniques. The experiments utilize 138 hot-wires in the mixing layer of an axisymmetric jet to simultaneously resolve the instantaneous streamwise velocity field at all locations. The POD is then applied to a double Fourier transform in time and azimuthal direction of the two-point velocity correlation tensor.

Measurements covered all the potential core region of the jet from 2 to 6 diameters downstream at various high Reynolds numbers, 78,400 to 156,800, and the far field region from 21 to 69 diameters downstream, at Reynolds numbers from 40,000 to 84,700. The results both illustrate the limitations of the previous work, and point the way for a significant breakthrough in our understanding of free shear flows.

Background

In an earlier version of this experiment that motivated the present work, Citriniti and George [2] obtained the dynamics of the flow from instantaneous realizations of the streamwise velocity field at $x/D = 3$ using 138 simultaneously-sampled hot-wire anemometer probes. They showed that only a few azimuthal Fourier modes and a single radial POD mode are necessary to represent the evolution of the eigenspectra of the turbulent field. Furthermore, the velocity reconstructions using the POD provided evidence for both azimuthally coherent structures that exist near the potential core, and for counter-rotating, streamwise vortex pairs (or ribs) in the region between successive azimuthally coherent structures, as well as coexisting for short periods with them.

The goals of this work were to extend the same methodology to different downstream positions and different Reynolds numbers, and to establish whether and how the jet structure could be changed by forcing.

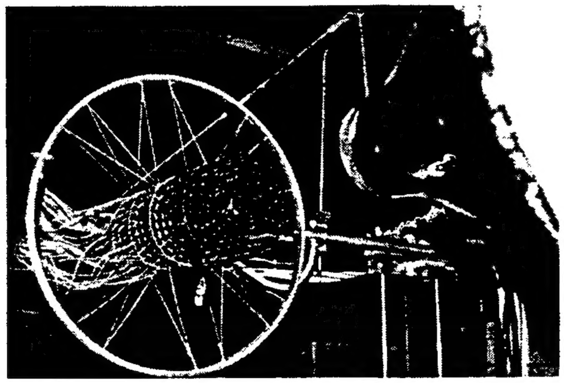

Figure 1: The 138 Hot-wire probe array

Progress in the Past Year

Data using the 138 hot-wire array (shown in figure 1) and the new data acquisition system have been taken over a wide range of Reynolds numbers and downstream positions. The mixing layer was investigated from 2 to 6 diameters downstream, with spacings of $0.5x/D$, and Reynolds numbers of 78,400, 117,600, and 156,800. We also investigated the far field region of the jet with 2 different jet diameters, taking 6 downstream positions from 21 to 69 diameters, and achieving Reynolds numbers from 40,000 to 84,700.

The mixing layer region ($x/D \leq 6$)

The lowest azimuthal mode for all POD modes, which dominated the dynamics at $x/D = 3$ in the previous experiments, dies off rapidly downstream. This is consistent with earlier studies of coherent structures which showed the evolution of more complex structures with increasing downstream distance. This trend toward homogeneity in the downstream evolution suggests that some residual value may control the growth rate of the far jet. On the other hand, for the higher azimuthal modes, the peak shifts to lower mode numbers and actually increases with downstream distance (see figure 2). These mixing layer data, normalized by shear layer similarity variables, $\lambda^{(n)}/(u^2 \cdot x/D)$ vs. $m \cdot x/D$ as presented on figure 3, collapse at all downstream positions and are nearly independent of Reynolds numbers. This is in contrast to the suggestion by [4] who expected that more complicated modal structures might evolve with increasing Reynolds number, but confirms the Reynolds number independence of the large scale structures for these high Reynolds numbers experiments as presumed by Glauser [3] and Citriniti and George [2].

The instantaneous fluctuating velocity field at each cross-section was reconstructed using the eigenfunctions and coefficients obtained from the projection onto the orig-

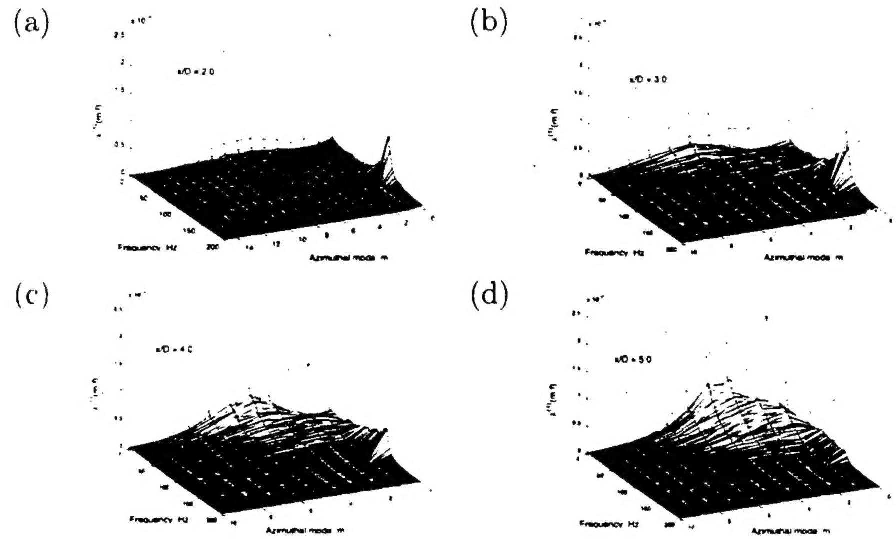

Figure 2: The first POD-mode $\lambda^{(1)}(m, f)$, distribution with azimuthal mode number, m, and frequency, f, for Re_D = 156,800, at different downstream positions: (a) x/D=2 , (b) 3, (c) 4, (d) 5

nal instantaneous velocity measured by all of the probes. Near the jet exit, highly organized and near-periodic evolutions of the large-scale structures are observed. The volcano-like eruptions identified by [2], dominate the dynamics and the interactions of the structures until about $x/D \approx 4$. After that, a "propeller-like" structure appears and dominates the pattern. For this experiment at least, these two and three-bladed "propeller-like" structures appear to rotate in a single direction. The direction of this rotation corresponds to the direction of a slight (1:1000) rotation at the exit plane of the jet, but the rate of rotation of the "propeller" is orders of magnitude faster.

The far field region ($x/D \geq 20$)

The first eigenspectrum, which contains more than 60% of the kinetic energy, was nearly independent of downstream position in the experiment considered. It was also identical to those obtained at the very end of the mixing layer region, and as well to those recently taken in the far wake of an axisymmetric disk. It presents two peaks: one at azimuthal mode-2 at near zero frequency, and the other one at mode-1 for a Strouhal number of around 1 (defined as St=fx/U_c, with x being the downstream position, and U_c the centerline velocity). The plots in figures 4 show these features clearly, since contour figures are presented alongside the 3D plots.

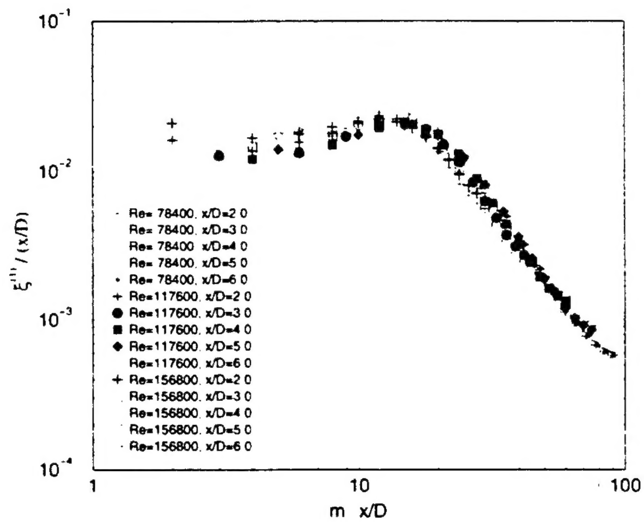

Figure 3: The first POD-mode energy distribution for the near jet normalized in shear layer variables, $(m \cdot x/D)$, at $Re_D = 78,400$, $117,600$, and $156,800$.

Conclusions and future work

A surprising feature of the present experiment was that the normalized eigenspectra did not depend on downstream distance after the end of the potential core region. This provides an important clue as to why and how equilibrium similarity governs the far jet, and also why the jet growth rate may reflect the upstream conditions.

The results presented here can be compared to analytical results of [1], and [5], all of whom predict an evolution from azimuthal mode-0 to mode-1 for a top-hat exit profile. We find a predominance of mode-2, suggesting that a linear stability analysis can be extended to a non-parallel free shear flow to predict this dominance of mode-2. This would certainly explain the similarity between the profiles taken at different downstream positions, and ones recently taken in the wake of an axisymmetric cylinder.

The last part of the investigation is the study of *how* an acoustic forcing could actually control and affect the jet mixing layer. The apparatus is currently being used. It seems, however, that the jet favors a propagation of mode-1, and/or mode-2 in the far field region, so it seems likely that the effect of any other kind of forcing will be dampened by the end of the mixing layer region.

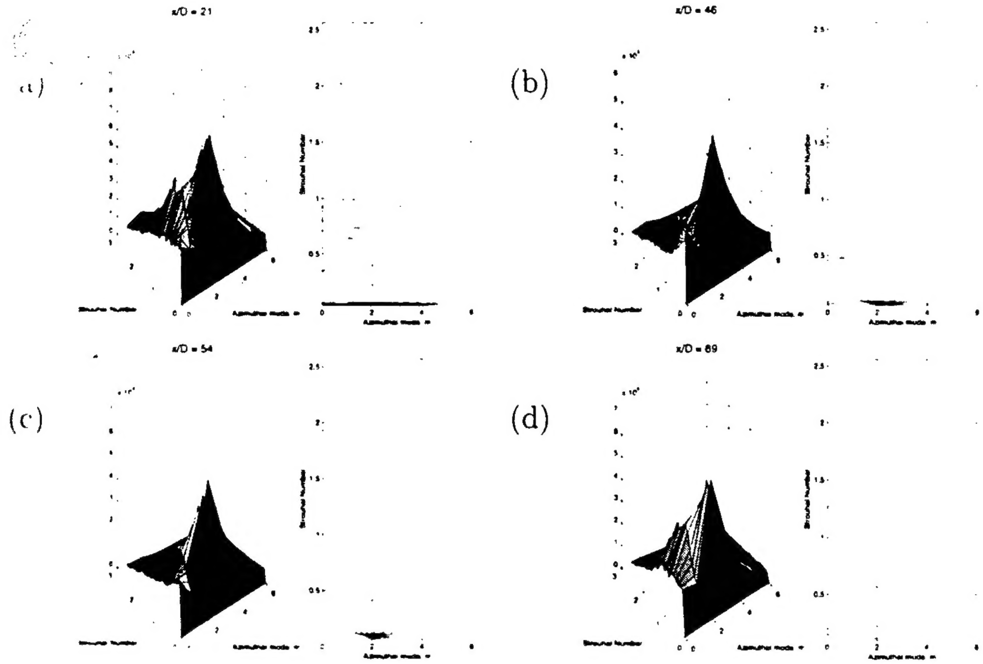

Figure 4: Eigenspectra for the far jet as functions of azimuthal mode number (m) and Strouhal number (fx/U_c) at different positions: (a) x/D=21 (Uo =50 m/s),and (b) 46, (c) 54, (d) 69, (last 3 at Uo=70 m/s)

Personnel

During the past year, the principal investigator of this research, William K. George, has moved to Chalmers University of Technology in Gothenburg, Sweden. He brought most of his experimental facilities, and several staff members. Stephan Gamard is a Ph.D. student who devoted all his time on this investigation since the beginning at Buffalo. In addition, they have been joined by Peter Johansson, a Ph.D. student at Chalmers, as part of a collaborative effort comparing axisymmetric jets and wakes. Scott Woodward, staff engineer and a principal in all of UB's POD investigations, is offering his assistance at Chalmers in the experimental aspects. Finally, Daehan Jung recently completed his Ph.D. on the mixing layer region of the jet, and has returned to the Korean Air Force Academy.

Publications from this work in the past year

- J.H. Citriniti and W.K. George, "Reconstruction of the global velocity field in the axisymmetric mixing layer utilizing the Proper Orthogonal Decomposition", *Journal of Fluid Mechanics*, 418:137-166, 2000.
- D. Jung, "An Investigation of the Reynolds-Number Dependence of the Ax-

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- D. Jung, S. H. Woodward, and W. K. George, "Evolution of the dynamics of a turbulent jet using the POD", *to be published in "Bulletin of the American Physical Society"*, 2001.
- S. Gamard, W. K. George, D. Jung, S. H. Woodward, "Results from using a 'slice' POD to investigate the dynamics of an axisymmetric turbulent jet", *to be published in "Bulletin of the American Physical Society"*, 2001.
- S. Gamard, D. Jung, S. Woodward, and W. K. George, "A POD application to the far field of an axisymmetric turbulent jet", *Submitted for publication to "Physics of Fluids"*.

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